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Development of a UV Communication Network
Using a Software Defined Radio

A Thesis submitted in partial satisfaction
of the requirements for the degree of

Master of Science
in
Electrical Engineering
by
Samuel Ibarra
December 2012

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To my family.
ABSTRACT OF THE THESIS

Development of a UV Communication Network
Using a Software Defined Radio

by

Samuel Ibarra

Master of Science, Graduate Program in Electrical Engineering
University of California, Riverside, December 2012
Dr. Gang Chen, Co-Chairperson
Dr. Ertem Tuncel, Co-Chairperson

Recently, research on the use of ultraviolet light for communication purposes has gained popularity. Analytical models that predict the manner in which UV light propagates and scatters have begun to be designed and developed. Using this information, a higher level network protocol can begin to be created that is able to take advantage of the unique properties of the UV channel. This thesis explores different aspects that comprise an outdoor UV communication network.

A leadership-based neighbor discovery protocol is developed that is able to handle the initial configuration of the communication system. The protocol creates an interference-free environment that helps reduce the time required for neighbor discovery. The protocol is based on the sequential discovery of a node’s neighbors. At the termination of the protocol, a node is able to know the addresses of the neighbors that surround it and the directions that it can use to communicate with them.

A medium access control protocol is proposed to moderate access to the medium making the communication among devices orderly and efficient. Practical UVOC-MAC is a random access based protocol designed for an outdoor ad hoc network. Practical UVOC-MAC is able to handle deafness and the hidden/exposed node problems that arise with the use of directional
antennas. The design of Practical UVOC-MAC is tied to the UV PHY layer properties which allow the use of non-line of sight links for communication. Spatial reuse is achieved by allowing the protocol to adaptively choose the direction of the communication.

A test bed is constructed allowing us to analyze the performance of the communication network. A software defined radio is used to construct transceivers that exchange information using the UV channel. A software framework is used to implement the neighbor discovery and MAC protocols. Preliminary results on the performance of the communication-system-tested bed are analyzed. The bit error rate and path loss are used to evaluate the performance of the communication network.
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Chapter 1 Introduction

1.1 Background

The ability to communicate has allowed the human race to develop into the diverse society that we see today. Communication has allowed the spread of information helping in the development of science and technology. Initially, communication consisted of speech and drawings giving humans the ability to exchange ideas and thoughts. As the human race developed, we were able to create the telegraph and phone allowing people to communicate at longer distances. Our current systems rely on the use of radio waves to transfer information from place to another. Radio frequencies have given us the ability to communicate wirelessly allowing the mobility of communication devices. The growing use of RF in mobile phones, satellites, radio stations, etc has also increased the demand for higher data rates. Thus, the radio spectrum has begun to become congested and unable to support larger capacities. Other forms of communication are needed in order to relieve some of the workload placed on RF systems.

Optical wireless communication has begun to appear as a possible alternative to radio frequency systems. Optical wireless communication consists of the use of the optical spectrum to transfer information. The optical spectrum is divided into three sections: infrared, visible light, and ultraviolet light. The wavelengths that each section covers can be seen in Figure 1.1. Optical communication has gained attention due to its unlicensed bandwidth, high power densities,
jamming resistance, and higher achievable data rates. Communication using optical light can therefore be considered a good option for future communication systems.

In this paper, I will focus on the use of ultraviolet light (UV-C) for communication purposes.

1.1.1 UV Channel Characteristics

As mentioned above, optical wireless communication can be achieved by using ultraviolet light as the communication channel. Ultraviolet light consists of the wavelengths within the 10 nm to 400 nm range of the optical spectrum. The UV spectrum can be divided into four sections consisting of UV-A, UV-B, UV-C, and Vacuum UV, as can be seen in Figure 1.1.

Both the UV spectrum and the UV-C band have a number of unique characteristics that have helped in their development as communication channels.

The UV-C portion of the UV spectrum covers the wavelengths within the 200 nm to 280 nm range. Ultraviolet light emitted by the sun within this range is greatly absorbed and attenuated...
by the earth’s ozone layer in the upper atmosphere. As a result, solar radiation at ground level within this UV band is considered low and negligible. Photodetectors operating at ground level in this band are able to detect low power UV signals with little to no background noise. Moreover, photodetectors with larger fields of view (FOV) can be developed without worrying about the introduction of additional background noise. A drawback of this band is that absorption continues to occur at lower levels of the atmosphere, which can be both a benefit and a problem. The problem occurs as the need for longer communication distances appears. The absorption limits the transmission distance that can be achieved by a transmission device. The limited communication distance is a benefit in that the transmitted signal will not be able to be detected outside the transmission range. We are therefore able to create a local communication link that is both secure and covert.

Scattering is another interesting characteristic of the UV spectrum that can be used to create non line of sight (NLOS) links for communication. We should remember that we are dealing with wavelengths that are commensurate with molecule and particle sizes. As a result, interactions between the molecules in the atmosphere and propagating UV waves occur. The interactions cause UV photons to scatter creating a number of diverse paths that a photon can take from a transmitter to a receiver. The diverse paths loosen the stringent requirements on pointing angles and alignment needed for transmitters and receive. Therefore, non line of sight (NLOS) links can be used for communication whenever line of sight (LOS) links are unable to be established.

As we can see, the unique characteristics of the UV spectrum allow it to become a valuable resource to consider for outdoor communication in rural or metropolitan settings. The NLOS links allow a communication channel to exist whenever LOS links are not able to be
established. The high absorption limits the communication distance, but helps create secure communication channels that can be used in both military and civilian applications.

1.1.2 UV Communication System
A typical UV communication system consists of a data source, a UV transmitter, the optical channel (free space), and a UV receiver, as can be seen in Figure 1.2 [11].

![Figure 1.2: Block diagram of a UV communication system](image)

A data source simply creates an electrical signal that contains information that needs to be transmitted. A UV transmitter converts the electrical signal into an UV signal that is modulated by the information from the data source. The signal then travels through the optical channel until it reaches the UV receiver. At the UV receiver, the signal is detected and demodulated, allowing the transmitted information to be retrieved.

1.1.2.1 UV Transmission Devices
As mentioned above, a UV transmitter converts an electrical signal into a UV signal using a light source. Light emitting diodes (LED), lasers, and laser diodes (LD) are typical light sources that are able to emit ultraviolet light. These light sources are able to be modulated at high rates, and can therefore serve as data transmission devices.

A light emitting diode consists of semiconductor junctions that emanate light when subjected to an electrical current. The wavelength that an LED produces is determined by its junction material. An LED is able to provide output powers between 1 to 10mW with light beams
that are relatively unfocused. The average output power can be increased to about 100mW by combining a number of LEDs in an array package [20]. Light emitting diodes have the advantage of being small in size and low power consumers. Lasers, on the other hand, can produce output power levels of about 0.1 to 1W, and have beams that are more focused and concentrated. A laser uses a gain medium, within its optical cavity, to amplify light of a certain wavelength. The wavelength a laser produces depends on the material that is selected as the gain medium. Lasers tend to be bulky, power hungry, and expensive when compared to diode sources. Laser diodes are devices that combine the properties of LEDs and lasers. LDs are semiconductor junction devices that have substrates that are etched or cleaved that help focus their light fields. LDs are able to achieve output powers of tens of milliwatts, and produce light beams that are more focused and concentrated than those of LEDs. The wavelength that a laser diode produces also depends on the material found at its junction.

1.1.2.2 UV Detection Devices
The detection of a UV signal is accomplished with the use of a UV receiver. A UV receiver converts a UV signal into an electrical signal that is used to retrieve the transmitted information. A typical UV receiver contains a receiver front end, an optical detector, and a post detection processor.

A receiver front end consists of a lens system that filters and focuses an optical signal. A lens system is able to filter out unwanted noise while allowing the desired wavelength to enter. The lens system is then able to focus the signal onto the smaller surface of the photodetector. A photodetector contains photosensitive material that produces a current or voltage in response to a received optical signal. Two commonly used photodetectors are photomultiplier tubes (PMT) and avalanche photodiodes (APD). Photomultiplier tubes are vacuum tubes that house a photocathode, dynodes, and an anode plate. In a PMT, a photon initially strikes a photocathode, producing an
electron of equal power. The electron then travels towards a cascade of dynodes that are used as electron multipliers to increase the number of free electrons. The electrons continue to move towards an anode plate where a current is produced indicating the arrival of the photon. PMTs have the advantage of having large detection areas, high gains, low dark currents, and bandwidths of about 100MHz. Avalanche photodiodes are semiconductor devices that have windows or openings allowing light to enter the device. When a photon hits the diode, a current is produced indicating the arrival of the photon. An avalanche photodiode uses avalanche multiplication to obtain a high internal gain. APD have a considerably small detection area and bandwidths of about 5Ghz. Avalanche photodiodes also have the advantage of having high quantum efficiency. Lastly, post detection processors attempt to retrieve the transmitted information by performing signal processing on the received signal. A post detection processor may also have the ability to amplify or filter a signal in order to improve its quality.

1.1.2.3 UV Modulation Schemes

In ultraviolet communication, the number of available modulation schemes is limited by the manner in which optical devices operate. Light sources, such as LEDs, emit non-coherent unipolar light signals that are unlike those created in RF systems. Moreover, photodetectors have outputs that are proportional to the instantaneous received power. Thus, phase information is not able to be obtained, and intensity variations are reflected by the change in received power. An intensity modulation (IM) and direct detection (DD) scheme is therefore a good option to consider for ultraviolet communication.

In intensity modulation, information is used to modulate the intensity of an optical source [11]. Two common forms of intensity modulation are on-off keying (OOK) and pulse position modulation (PPM). On-off keying encoding uses two quantization levels to represent bits “1” and “0”. A pulse is used to represent a binary 1, while the absence of a pulse represents a binary 0. At
the detector, a threshold detection scheme is implemented that allows a receiver to reliably
distinguish between the two quantization levels. On-off keying is able to tackle pulse broadening
caused by multi-path dispersion, making it a good option for NLOS communication [18].
Moreover, the ability to rapidly switch on or off an optical source allows OOK to achieve high
source bit rates. In pulse position modulation, information is transmitted by sending a single pulse
during a PPM frame [11]. A PPM frame consists of a number of adjacent time slots that
represent different data words. The location of the pulse within the set of time slots determines
the data word that was transmitted. The size of the data word and the number of available time
slots depends on the number of bits that need to be transmitted. Data words containing M-bits are
able to be transmitted using $2^M$ time slots. The receiver, in this case, would be implemented using
a maximum likelihood scheme that would reliably identify the presence of a pulse. The use of a
single high peak power pulse allows us to obtain a low average power. The main disadvantage
with PPM is that time synchronization between the transmitter and receiver is needed. If proper
synchronization is not achieved, then an accurate time location for the pulse will not be obtained.

1.2 Motivation
Research regarding the characteristics of the UV channel has gained popularity in recent
years. Analytical models that predict the manner in which UV light propagates make the
implementation of a communication system possible. The path loss that is experienced in the UV
channel can be accurately measured, giving us a better understanding of the achievable
transmission range. Furthermore, models that account for the multiple scattering of UV light
have also begun to be designed. Using this information, a higher level network protocol can begin
to be created which is able to take advantage of the UV channel characteristics.

The unique characteristics of the UV spectrum make it a good candidate to consider for
an outdoor communication system. An outdoor UV communication system that is able to
function alongside an existing RF system would be of great interest for ground troop communication. Moreover, in a military setting, a system would need to be rapidly deployed and configured. A distributed communication protocol would therefore be preferred over an infrastructure based protocol. Unfortunately, research about distributed optical communication protocols is very limited.

The IEEE 802.11 standard is a proposed MAC scheme that is based on the use of CSMA/CA. The information is transmitted omni-directionally allowing neighbors to become aware of ongoing communications. Optional ready to send (RTS) and clear to send (CTS) messages can be used to reserve the communication channel. The IEEE 802.11 standard is able to support physical layers that operate within the infrared spectrum. Alr [31] has also been developed, and it is specifically made to operate within the IR spectrum. Although Alr is similar to the standard, higher data rates have been achieved during its simulation.

Information on distributed protocols based on radio frequency is more abundant. Due to manner in which light sources operate, an ad hoc protocol that uses directional antennas (DA) is a more viable option. In [35], a protocol based on the usage of two types of RTS/CTS messages is proposed. The first type of RTS/CTS message is sent directionally to initiate the communication, while the second type is sent in a circular manner alerting neighbors of the intended communication. CRM, CRC, MDA, and DMAC/ DAC [6, 17, 12, 29] also propose protocols that operate by transmitting circular RTS/CTS messages. The usage of circular RTS/CTS messages is not a practical option to consider for an optical system. LEDs provide the ability to operate as both directional and omni-directional transmitters under certain configurations. Tone DMAC is proposed in [4]. In Tone DMAC, an omni-directional out band tone is transmitted in order to help neighbors distinguish between deafness and network congestion. Out of band tones would
require the usage of different filters and additional hardware in an optical system. The additional
hardware would not allow the construction of a communication system that is practical in real life.

Research about distributed neighbor discovery protocols that allow the initial
configuration of a optical communication system is also very limited. Certain MAC protocols that
were mentioned earlier [6, 17, 12, 29], provided some form of neighbor discovery. Neighbor
discovery is typically achieved by using receivers that are able to steer their antennas in the
direction of the received signal. The direction is then recorded, and used later whenever
information needs to be exchanged. In an optical system, mechanical operations would be needed
in order to allow a photodetector to scan the medium. In [28], a handshake based neighbor
discovery protocol is proposed. Within this protocol, nearby neighbors are initially discovered.
The transmission power is then increased allowing more distant neighbors to be detected. Each
node is assumed to be equipped with GPS or an inertial navigation system (INS).

Due to unique characteristics of the UV channel, the protocols mentioned above cannot
be directly applied to an optical communication system. The scattering experienced by the UV
channel should be used to create non-line of sight links when line of sight communication is not
possible. This thesis will focus on the design of MAC and neighbor discovery protocols that are
able to operate within the UV spectrum. Our protocols are based on earlier work performed by
Yiyang Li at the University of California, Riverside [20, 21, 22]. Modifications have been
performed that allowed the protocols to be implemented within a software framework.
Transceivers that are able to operate within such a network are constructed. In order to understand
the performance of these protocols, a test bed is constructed. A number of experiments are
performed allowing us to analysis the operation and performance of the optical system.
1.3 Contributions and Outline of the Thesis

The remainder of this thesis is organized as follows:

Chapter 2 introduces a medium access control (MAC) protocol designed for an ultraviolet communication system (Practical UVOC-MAC). The design of the transceiver (node) that will be used in the communication system is presented. A brief overview of the operation of Practical UVOC-MAC is then given. The different operational states in which a transceiver (node) could find itself in are presented. The author continues by giving a detailed explanation of different data structures that are maintained, and procedures that occur within Practical UVOC-MAC.

Chapter 3 covers a leadership based neighbor discovery protocol that allows the initial configuration of a communication system. The author begins by providing information on the operation of the neighbor discovery protocol. The author continues by giving an explanation on different procedures that constitute the neighbor discovery process.

Chapter 4 gives a detailed explanation on the construction and implementation of the communication system. The construction of the transceiver is initially covered. An overview of the hardware components that comprise our transmitter and receiver paths is then given. The manner in which the information is transmitted and received within the software is reviewed. Information and details on the different hardware and software components that are used are presented.

In Chapter 5, preliminary results on the performance of the communication system are presented. The system and experimental setups are reviewed. The results of the different experiments that were performed are then covered. The author concludes by highlighting the content that was covered in this thesis.
Chapter 2 Practical UVOC-MAC Protocol Design

2.1 Practical UVOC-MAC Design

In this section, we introduce our proposed ultraviolet medium access control protocol that is implemented in our communication system. We designed our MAC protocol in a way that takes into account the unique properties of the UV channel. We are therefore able to take advantage of the NLOS links that are created and use them for communication. Our proposed MAC protocol allows us to reduce the effects of problems such as deafness and hidden/exposed nodes that commonly occur with the use of directional antennas. Moreover, the practicality of the MAC protocol allows a real world implementation of both the procedure and the system.

2.1.1 Practical UVOC-MAC Transceiver Design

The goal is to design a practical system that could be used for communication in unattended ground sensing networks or in battlefields by soldiers. Therefore, it is necessary to design a transceiver that is able to operate in these conditions. In order to accomplish this, our transceiver is designed after a previously proposed indoor visible light communication system that provided the flexibility and characteristics that were needed [25]. The design of the transceiver can be seen in Figure 2.1.
In Figure 2.1, the dots in the surrounding sides of the transceiver represent LED transmitters. A dot could be a single LED or could consist of multiple LEDs transmitting simultaneously. By transmitting in a single direction, the transceiver becomes a directional transmitting device. The node can simultaneously transmit in every direction creating an omni-directional transmitting device. The dot facing upwards represents a photon detecting device such as a PMT or APD. Due to this arrangement, the transceiver becomes an omni-directional receiving device. The configuration of the transceiver allows the system to be easily installed and deployed on a vehicle or a soldier’s helmet. The configuration also allows the use NLOS links as the main communication channel.

The number of directions that a transceiver can have is determined by the beam angle of the LEDs. For example, if the beam angle of an LED is 18 degrees, then the transceiver will have 20 directions which are enough to cover its surroundings [20]. Therefore, as the beam angle decreases the number of directions a transceiver needs to cover its surroundings increases. The same applies for an increasing beam angle. As the beam angle increases, the number of directions needed to cover a transceiver’s surroundings decreases.

Our transceivers are implemented by using a software defined radio named USRP. We developed UV daughterboards that are able to interface with the USRP, and allow us to use LEDs
as transmitters and PMTs as receivers. We will talk further about the implementation of our system in Chapter 4.

2.1.2 Practical UVOC-MAC Description

Our system implements Practical UVOC-MAC which is a random access based protocol designed for an ultraviolet outdoor ad hoc network. Practical UVOC-MAC was developed with the properties of the UV channel in mind which helps enhance the performance of our system.

Practical UVOC-MAC allows us to take advantage of spatial reuse by adaptively choosing the direction of the desired communication. By doing so, we are able to have multiple transceivers communicating with each other within a given area. Our protocol is also able to reduce the effects of deafness and the hidden/exposed node problems that appear when directional antennas are used.

We will begin by giving a functional description of the MAC protocol and then continue with a more detailed explanation.

2.1.2.1 Practical UVOC-MAC Overview

We will refer to an individual transceiver as a node for the continuation of this paper.

A node is assumed to contain information regarding the number of neighbors that surround it, the addresses that identify them, and the directions that can be used to communicate with them. This information can be obtained with the use of a neighbor discovery protocol. The neighbor discovery protocol that is implemented in our system is introduced in Chapter 3. A node is considered available if it is not part of an ongoing communication. An available direction is a direction that will not cause interference to any other ongoing communication.

- A node begins its operation by being in an Idle state where it simply listens to the medium and decodes any information it receives.
• Once a node has new data to send, it checks its tables (discussed later) to make sure that the destination node is available. The node also checks to see which of its neighbors are currently unavailable due to ongoing communication.

• The source node then transmits a request-to-send (RTS) message in every available direction. If the destination node is not available, the source node will wait until the node becomes available to send the RTS message.

• After transmitting the RTS message, the node enters the Wait for CTS state. In this state, the node listens to the medium and waits to receive a clear-to-send (CTS) message in response to the RTS message that was sent. A node will remain in this state until it experiences a CTS timeout or a CTS message is received. If the node experiences a CTS timeout, the node will attempt to resend the RTS message at a later time.

• Upon receiving the RTS message, the destination node checks its tables to see which of its neighbors are currently unavailable. The destination node then replies to the source node by transmitting a CTS message in all the available directions.

• The destination node then transitions to the Receive Data state. In the Receive Data state, the node will be able to update its tables using any information that it receives while it listens to the medium waiting to receive the data.

• After receiving the CTS message, the source node then checks its tables once more and selects the best direction to use to communicate with the destination node. After choosing the best direction, the source node transitions to the Send Data state where it begins to transmit the pending data. After transmission, the source node returns to the Idle state.

• Once the destination node has received the data, the node returns to the Idle state. If the node does not receive any data, the node will simply return to the Idle state.
The RTS and CTS messages that are exchanged are similar to those proposed in the IEEE 802.11 standard. Although we have made certain modifications in order to enhance the performance for our system. The RTS and CTS messages are transmitted in every available direction. By transmitting the messages omni-directionally, the nodes in the neighborhood are informed of the communication that will take place. The neighboring nodes are therefore able to update their tables containing their neighborhood information. The omni-directional CTS and RTS messages also serve to combat the deafness and hidden/exposed node problems that arise.
Data is sent directionally in order to reduce interference in other ongoing neighborhood communications. The state transition diagram for Practical UVOC-MAC can be seen in Figure 2.2.

2.1.2.2 Description on Tables

We will now describe in greater detail the tables that were mentioned in the previous section. We will also explain how these tables are created and maintained within each node. Figure 2.3 presents the structures of the Connection Table and Receiving Nodes Table.

![Figure 2.3: Structure of Connection Table (top) and Receiving Nodes Table (bottom)](image)

**Connection Table**: The table contains all the addresses of the neighboring nodes and the directions that a node can use to communicate with them. The Connection Table is constructed during the neighbor discovery process. During the neighbor discovery process, a node associates a neighbor with a specific direction. The neighbor’s address and associated direction are then placed into the Connection Table. The Connection Table continues to be updated until all the surrounding neighbors are discovered. In order to ensure the optimal direction for a particular communication exchange is selected, the directions are ranked in ascending order. The method that is used to rank the directions is also given in Chapter 3. The table continues to be updated frequently in order to give a node the most current information.
Receiving Nodes Table: The table contains a list of neighboring nodes that are currently part of an ongoing communication. The table also contains the duration the neighbors will remain engaged in the current communication. The Receiving Nodes Table is updated whenever a package is received. From the package, a node is able to obtain the source id, destination id, and duration for the intended communication. The node then sets a timer for the duration and marks a neighboring node as busy during that period of time. The Receiving Nodes Table is also constructed during the neighbor discovery process. The information within this table helps prevent nodes from interfering with neighboring node’s communication. The table also helps combat the effects of deafness.

Check Table Procedure

The check table procedure occurs whenever there is new data or a CTS message is to be sent. In the first case, a node checks the Receiving Nodes Table in order to see which of its neighbors are currently available. The node also checks the Connection Table and retrieves the directions of the available nodes. The node then proceeds to send an RTS message in every available direction. Once the node receives a CTS message, it checks its Connection Table in order to select the best available direction to communicate with the destination node. If a CTS message is to be sent in response to an RTS message, the node checks its Receiving Nodes Table in order to see which of the neighboring nodes are currently available. The Connection Table is also checked in order to retrieve the directions of the available nodes. The node then proceeds to transmit a CTS message in all the available directions.
2.1.3 Frame Structure

<table>
<thead>
<tr>
<th>Frame Control</th>
<th>Source ID</th>
<th>Destination ID</th>
<th>Direction ID</th>
<th>Packet Type</th>
<th>Duration</th>
<th>Frame Body</th>
<th>FCS</th>
</tr>
</thead>
</table>

Figure 2.4: Frame structure of Practical UVOC-MAC packet

The frame structure of a Practical UVOC-MAC packet can be seen in Figure 2.4. The Source ID field specifies the source node’s address. The Destination ID field contains the address of the node that is trying to be reached at the destination. The Direction ID is used to inform the destination node of the direction that will be used to transmit the pending data. The Packet Type field states the type of packet that is transmitted (CTS, RTS, or Data). The Duration field specifies the duration of the intended communication. The Frame Body field contains the data that the node is trying to send to the destination node.

2.2 Summary

In this chapter, we presented our proposed Practical UVOC-MAC protocol. The unique properties of the UV channel are taken into account in order to increase the performance of our system. The Practical UVOC-MAC protocol is able to use NLOS links as the main communication channel. Practical UVOC-MAC is also able to adaptively select the direction of the desired communication in order to reduce the overall interference experienced in the network.

The design of Practical UVOC-MAC can be further developed in order to increase its performance and versatility. Full duplex communication can be considered in order to increase the throughput of the communication channel. Practical UVOC-MAC can also be modified to account for node mobility within the network.
Chapter 3 Practical Leadership Based Neighbor Discovery Protocol Design

3.1 Neighbor Discovery Design
A neighbor discovery protocol allows the initial configuration of a communication system before the network begins its operation. In the previous chapter, we mentioned that our system is designed to operate in a military setting. More specifically, our system is intended to be used by soldiers on a battlefield or as an unattended ground sensing network. In these settings, a system needs to be able to be rapidly deployed and configured in order to effectively accomplish its objective. A distributed neighbor discovery protocol would therefore be preferred over an infrastructure based protocol.

In this section, we introduce our proposed neighbor discovery protocol. Our neighbor discovery protocol allows the nodes in a network to determine the existence of its surrounding neighbors and the directions that it can use to communicate with them. At the end of the neighbor discovery process, a node will be able to communicate and share information with its neighboring nodes.

3.1.1 Neighbor Discovery Description
We designed our Practical Leadership Based Neighbor Discovery protocol with the properties of the UV channel in mind. The NLOS links that are created in the UV channel are
used as the primary communication medium. The nodes in the network communicate with each other by transmitting directionally and receiving omni-directionally.

Our protocol consists of the sequential discovery of nodes within the network. A single node, called the leader, begins operations by performing the neighbor discovery process. Once the leader has finished, a successor is selected that continues the neighbor discovery process. The procedure continues until all the nodes have had the opportunity to become the leader, and every node in the network has been discovered.

In this protocol, a node is assumed to contain a unique identifier address and information regarding the structure of the packets that are used during neighbor discovery. The identifier address allows the nodes to distinguish themselves from one another. A node is assigned an address before it begins its operation. The frame structure allows a node to decode any information it receives. The protocol uses request, feedback, and notify packets (discussed later) during the neighbor discovery process. A node is not aware of the number of neighbors that surround it, the addresses that identify them, or the directions that can be used to communicate with them.

We will begin by describing the operation of the neighbor discovery protocol, and then continue with a more detailed description of the different data structures and procedures contained within the protocol.

3.1.2 Neighbor Discovery Protocol
The neighbor discovery protocol operates as follows:

- Initially, nodes are in a Standby state where they simply listen to the medium and decode any information they receive.
• A preselected leader node initiates the neighbor discovery process by sending a request packet in a randomly selected direction. The request packet contains the address of the leader, the direction that is used for the transmission, and the time a neighbor should wait before it responds.

• After transmitting the request packet, the leader switches clockwise to the next direction, and transmits the following request packet. The process continues until the leader has sent a request packet in every direction.

• Once the leader has finished transmitting the request packets, the leader enters the Wait for Feedback state. In this state, the leader node simply listens to the medium and waits to receive feedback packets from any neighbors responding to its request packets.

• When a neighbor receives a request packet from the leader, the neighbor sets a timer and waits for the period of time specified on the request packet.

• After the timer expires, the neighbor responds to the request packet by transmitting an omni-directional feedback packet. The feedback packet contains the address of the responding node, and the direction that the leader used to send the request packet.

• Once the leader node has finished waiting for feedbacks, the leader creates a list containing the neighbors it discovered, and the directions it can use to communicate with them (Connection Table). The leader then randomly selects a successor from the list mentioned above. The leader proceeds to send a notify packet to its successor making it aware that it has been selected as the new leader.

• After sending the notify packet, the leader node returns to the Standby state.

• Upon receiving the notify packet, the newly selected leader continues with the neighbor discovery process.
The notify packet may at some point get lost during its transmission to the leader’s successor. If this occurs, the leader has the ability to resend the notify packet. The leader will resend the notify packet if it does not receive a request from its successor for a period of 2T. The leader will reselect a new successor and retransmit the notify packet. The leader will continue this process until it is able to successfully transfer its leadership role to another node. Figure 3.1 shows the transitions diagram of the neighbor discovery protocol.
3.1.3 Fairness

In order to obtain all of its neighborhood information, it is likely that a node may have to serve as the leader multiple times. Only then would it be safe to assume that a node has been able to collected all of its neighborhood information. A fairness problem can arise as nodes begin to serve as the leader more than once. Certain nodes may be selected more often than others to obtain the leadership role. Therefore, the leader should have a way to select a node that has served as the leader the least number of times to be its successor.

We accomplish this by maintaining a leadership counter in each node. The leadership counter allows a node to keep track of the number of times it has served as the leader. Every time a node serves as the leader, the leadership counter will be incremented by one. A node records this information onto the Leadership Table. The Leadership Table contains a record of the number of times that each node in the network has served as the leader. The Leadership Table is included within the notify packet in order to allow the current leader to have the most up to date information. Having this information, the leader is able select a node that has served as the leader the least number of times.

3.1.4 Termination of Neighbor Discovery

As mentioned above, a node has the opportunity to assume the leadership role multiple times. A leader node is therefore able to update its neighborhood information every time it becomes the leader. If a leader node is unable to obtain new neighborhood information, then it is safe to assume that the leader has finished discovering all of its neighbors. The leader node is then able to mark itself has being finished with the neighbor discovery process, after it is unable to obtain new neighborhood information after a certain number of consecutive times. Once all the nodes have marked themselves has being finished with the neighbor discovery process, the procedure can be terminated.
The termination of the neighbor discovery process is implemented by maintaining a termination counter in each node. The termination counter allows a node to keep track of the number of times the node has been the leader and has not been able to obtain new neighborhood information. The counter is reset every time the leader is able to obtain new neighborhood information. Once the termination counter reaches a predefined threshold, the node marks itself as being finished with the neighbor discovery process. The Leadership Table is used to keep track of the nodes that have marked themselves as being finished with the neighbor discovery process. The Leadership Table mentioned in this section is the same table that was introduced in the previous section. After a node has marked itself as being finished, the node will no longer be considered to serve as the leader. Once the final node has marked itself as being finished, the neighbor discovery process is terminated, and the network begins its operation. The Leadership Table can be seen in Figure 3.2.

### 3.1.5 Frame Structure

The structure of the request, feedback, and notify packets can be seen in Figure 3.3. In the request packet, the Source ID field specifies the leader node’s address. The Direction ID field specifies the direction the leader is using to transmit the request packet. The Packet Type field states the type of packet that was sent, in this case a request packet. The Time to Wait field tells a neighboring node the time it should wait before it responds with a feedback packet.

The feedback packet contains a Destination ID field which has the address of the neighbor node that is responding to the request packet. The Source Direction ID field specifies
the direction that the leader initially used to transmit the request packet. The Packet Type field simply states that a feedback packet that was sent.

![Frame structure of request (top), feedback (middle), and the notify packet (bottom).](image)

The Source ID field in the notify packet specifies the leader node’s address. The Destination ID field contains the address of the neighbor that was selected as the leader’s successor. The Direction ID field specifies the direction the leader is using to transmit the notify packet. The Packet Type field states that the packet is a notify packet. The Leadership Table field contains the number of times that each node has served as the leader, and the nodes that have marked themselves as being finished with neighbor discovery.

### 3.1.6 Ranking of Directions

During the neighbor discovery process, it may also be possible that a leader is able to communicate with a neighbor in more than one direction. Communication in multiple directions is due to the fact that we are using NLOS links for communication. A number of communication links appear in different directions that can be used to exchange information from one neighbor to another. In order to distinguish the best direction that can be used to communication with a neighbor, the leader will have the ability to rank the different directions. The directions are
ranked based on their signal strength. As the leader enters the Wait for Feedback state, it will record the power levels it experiences after receiving each feedback packet. If the leader receives another feedback packet from the same neighbor in a different direction, the leader will compare the two power levels. The direction with the highest received power is then ranked has the highest quality communication link. This direction will be the primary communication link that a node will use to communicate with its neighbor. A node will still have the ability to use a lower ranked direction for communication if it fails to establish a link using the highest ranked direction. The directions are recorded on the Connection Table that was introduced in the previous chapter in the order of their rank. A node is able to use this information once the network is configured and begins its operation.

3.2 Summary

In this chapter, we presented our proposed Practical Leadership Based Neighbor Discovery protocol. The unique properties of the UV channel are taken into account in order to use NLOS links as the primary communication channel. Our neighbor discovery protocol allows us to efficiently configure a network before it begins operation. The protocol also allows the discovery of nodes in a network while creating an interference free environment.

The design of our Practical Leadership Based Neighbor Discovery protocol can be further developed in the future in order to increase its efficiency. The neighbor discovery protocol can be designed to account for node mobility. The protocol can also be modified in order to decrease the overheard experienced during the neighbor discovery process.
Chapter 4 UV Communication System Design and Implementation

4.1 UV System Design

Our UV communication network consists of the different components that were given in the previous two chapters. The transmission and reception of signals is achieved with the use of the transceiver introduced in Chapter 2. A number of these transceivers allow us to create an ad hoc network that can be randomly deployed in an outdoor setting. The initial configuration of the system is handled by the neighbor discovery protocol. The protocol allows nodes to determine the existence and location of their surrounding neighbors. Lastly, Practical UVOC-MAC is used to moderate the access to the medium making the communication among devices orderly and efficient.

The implementation of such a communication system is not a trivial task. A number of system and physical level parameters needed to be considered before the construction of the system could begin. At a system level, we wanted our system to be small and portable allowing it to be carried by soldiers on a battlefield. The communication system needed to be robust and durable in order to operate in tough outdoor conditions. The system also needed to be flexible enough to endure future system upgrades or changes in operation. Creating a system that was
covert was also important in order to prevent others from receiving or jamming the signal. The overall cost and complexity needed to be low in order to allow its real world implementation. At the physical level, our system needed to be able to support transmitters and receivers with wide fields of view. The system should also be able to operate within the safety regulations placed by government agencies. Furthermore, our system needed to operate in a manner that allowed us to minimize the bit error rate that the system experienced.

These parameters served as a starting point allowing us to construct a communication system that could be used in real life.

4.2 Implementation of Transceiver Design

The implementation of our ultraviolet communication system consists of two parts: the development of the transceivers and the creation of the neighbor discovery and MAC protocols. In this section, we focus on the construction of the transceivers. We give details on how the design of the transceiver was implemented. We also introduce the different hardware components that are used, and explain how they were integrated into the communication system.

4.2.1 Transceiver Shape Design

In Chapter 2, we introduced the transceiver shape that was selected for our implementation. The shape consists of a polygon base with walls attached at every side (Figure 2.1). The LED transmitters are mounted on the walls, each facing a different direction. The transceiver can serve as a directional transmitting device when a single LED is turned on or as an omni-directional transmitting device when all the LEDs are on. The beamwidth of the LEDs determined the number of directions that our transceiver must have. In order to increase the beamwidth of our transmitters, we decided to attach two LEDs in every direction. With this configuration, we determined that a five sided transceiver would be enough to cover our surroundings. We began construction of our transceiver by cutting out a pentagonal shape for our
base. The base was cut out of sheet metal that we obtained from our local hardware store. We also created rectangular walls, using sheet metal as well, that were mounted onto the base using nuts and bolts. We drilled two holes in every wall that are used to house the LEDs. Moreover, the transceiver also consists of a photodetector facing upwards allowing it to operate as an omni receiving device. We decided that mounting the photodetector on a separate stand would be a better option for our test bed. A separate stand would allow us to adjust the angle of the PMT during experimentation. Figure 4.1 shows an image of our finished transceiver.

Figure 4.1: Image of network transceiver
4.2.2 Hardware Transmitter Design

Figure 4.2 shows the structure and the different components that compose our transmitter chain.

![Transmitter Diagram](image)

Figure 4.2: Structure of transmitter chain

4.2.2.1 Universal Software Radio Peripheral

The Universal Software Radio Peripheral (USRP) is a software defined radio (SDR) developed by Matthew Ettus. Software defined radios allow you to use software to implement functionalities that are typically handled by physical layer components. Components such as modulators, demodulators, filters, and amplifiers are implemented using software instead of specialized circuitry. Using software to implement hardware components, allow communication systems to be rapidly designed and developed. Moreover, hardware changes are not needed whenever the operation of the system changes. Developers are able to make upgrades to a communication system without having to worry about the additional cost of time or money.

For our implementation, we used the USRP N210 made by National Instruments to serve as our transceiver. The USRP N210 consists of a Xilinx Spartan 3A-DSP FPGA core, dual 100MS/s analog to digital converts, dual 400 MS/s digital to analog converts, and a gigabit Ethernet connection used to stream data to and from a host computer [36]. The USRP N210 is able to operate within the DC to 6 GHz range. Moreover, the N210 provides an expansion port that can be used to connect and synchronize multiple USRPs for MIMO operation. Firmware is loaded onto the FPGA with the use of the Ethernet connection. The USRP also contains interface
slots that are used to connect transmitter and receiver daughterboards. The daughterboards have
the capability of serving as either transmitter or receiver RF front ends. Signal processing
functionalities that are needed to run the USRP are provided by GNU Radio. GNU Radio is an
open source software developed to work with software radios or in simulation like environments.
Other programs, such as Labview or Matlab, can also be used with the USRP which provide
similar functionalities. The overall versatility, low cost, and open source software made the USRP
a good option for our implementation.

The USRP N210 served has the data source and transmission/reception device for our
communication system. Initially, data is constructed within our host computer. The data is then
placed within one of the packets that was mentioned in the previous chapters. The information is
then processed and modulated using the different signal blocks provided by GNU Radio. The
information is then transferred via Ethernet from the host computer to the USRP. Once the
information is received at the USRP, the information is processed further by the FPGA, and
converted to an analog signal using DACs. At this point, the analog signal is given to the
transmitter daughterboard connected to the USRP.

4.2.2.2 Transmitter Daughterboards
   As mentioned above, the USRP contains interface slots that allow transmitter and
receiver daughterboards to be connected. The transmitter daughterboards serve as RF front ends
converting baseband signals to a desired frequency band. A number of different daughterboards
are available that are able to function at different frequencies. Certain daughterboards provide a
full working front end while others provide raw signals allowing an external front end to be
connected. Some of the daughterboards and their characteristics can be seen in Figure 4.3
<table>
<thead>
<tr>
<th>Daughterboards</th>
<th>Freq Range</th>
<th>Mode Of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Tx</td>
<td>1-250 MHz</td>
<td>Tx</td>
</tr>
<tr>
<td>Basic Rx</td>
<td>1-250 MHz</td>
<td>Rx</td>
</tr>
<tr>
<td>LFTX</td>
<td>0-30 MHz</td>
<td>Tx</td>
</tr>
<tr>
<td>LFRX</td>
<td>0-30 MHz</td>
<td>Rx</td>
</tr>
<tr>
<td>DBSRX2</td>
<td>800-2300 MHz</td>
<td>Rx</td>
</tr>
<tr>
<td>XCVR2450</td>
<td>2.4 GHz - 2.5 GHz, 4.9 GHz to 5.9 GHz</td>
<td>Tx/Rx</td>
</tr>
<tr>
<td>RFX900</td>
<td>750-1050 MHz</td>
<td>Rx/Tx</td>
</tr>
<tr>
<td>RFX1800</td>
<td>1.5 - 2.1 GHz</td>
<td>Rx/Tx</td>
</tr>
<tr>
<td>RFX2400</td>
<td>2.3-2.9 GHz</td>
<td>Rx/Tx</td>
</tr>
</tbody>
</table>

Figure 4.3: USRP daughterboard provided by Ettus Research

We selected the LFTX and LFRX daughterboards for our implementation. The LFTX functions as a transmitter daughterboard able to operate within the DC to 30 MHz frequency band. The LFTX is one of the daughterboards that does not provide an RF front end. Its ability to provide a raw signal allowed us to construct our own front end that was capable of transmitting our information using LEDs. The LFTX daughterboard also provides a number of control pins that connected to I/O ports on the FPGA. These control pins can be controlled by using special commands found in the GNU Radio software. The pins can be used for either input or output, and can be used to function with external front ends.

The LFTX daughterboard served as our transmitter front end providing us with a raw signal that we were able to modify. The output of the daughterboard connects to the LED
interface board. The control pins were used to control the direction that was used for a particular transmission. Further details on how this was done are given in the following section.

**Figure 4.4: LFTX (right) and LFRX (left) daughterboards [19]**

### 4.2.2.3 LED Interface Board and LED Driving Board

The LED interface board consists of a Microchip TC4428 chip that operates as a charge pump. The TC4428 chip is able to increase the voltage of the signal that enters the circuit. The signal from the interface board is then divided into five separate lines. The five signal lines connect to an analog switch. The analog switch allows us to control the number of lines that are used during each transmission. The analog switch is controlled by the controlled pins introduced in previous section. Five control pins are used which allows us to control each individual line. When the logic at the control pin is 1, the switch is enabled and the signal is able to enter the LED driving circuit. When the logic at the control pin is 0, the switch is disabled and the signal is blocked from entering. The directions that are used for a certain transmission can therefore be selected by changing the logic of the control pins. Each one of the signal lines is used to drive one pair of LED transmitters. In the driving circuit, the LEDs are placed in a common source amplifier configuration. The minimal delay and higher current allows the LEDs to be driven at maximum capacity.
The final component of our transmitter chain consists of our LED transmitters. Our LED transmitters are UVTOP250 AIGaN LEDs manufactured by Sensor Electronic Technologies. The LEDs have a center wavelength of 250 nm allowing them to operate within the solar blind region of the UV spectrum. The LEDs have a hemispherical lens which helps concentrate the light beam, and reduces the beamwidth to about 10 degrees. The LEDs have a half width spectrum of about 12 nm. The LEDs also have an output power of 0.5mW while dissipating 150mW of power. The temperature of the LEDs should be monitored during their operation in order to prevent damage from occurring. The LEDs allow us to create a UV signal that carries the information. Figure 4.5 shows an image of our transmitter chain.

Figure 4.5: Image of transmitter chain
4.2.3 Hardware Receiver Design

The structure of the receiver chain can be seen in Figure 4.6

![Diagram of receiver chain]

Figure 4.6: Structure of receiver chain

4.2.3.1 Photodetector and Post Amplifier

Our receiver chain begins with the use of a Perkin Elmer PMT. The PMT contains photosensitive material that produces a current in response to a received optical signal. The current response is proportional to the number of received photons. The spectral response of the PMT ranges from 160 to 310 nm. In this range, the PMT is able to provide 10 dark counts per second, and a dark current of 100pA. The quantum efficiency at 200 nm with a gain of $10^6$ is estimated to be 15%. In order to reduce the spectral response of the photomultiplier, we installed a solar blind filter that suppresses out of band noise. The filter is centered at 255 nm, and has a passband peak transmission of 10%. The characteristics and availability of both the PMT and solar blind filter made them good options for our implementation.

The receiver chain continues with the output of the PMT being connected to a low noise current preamplifier. The current preamplifier that was selected was a Model SR570 developed by Stanford Research Systems. The preamplifier provides an output voltage that is proportional to input current. The device has a sensitivity range of 1pA/V to 1mA/V. The device also allows a user to select between low noise, high bandwidth, and low drift settings. The flexibility and versatility of the device made it ideal for our implementation. Moreover, the preamplifier allowed us to convert the current signal of the PMT to a voltage signal that the USRP could detect.
4.2.3.2 Receiver Daughterboards and Universal Software Radio Peripheral

As mentioned previously, we decided to use the LFRX daughterboard for our implementation. The LFRX daughterboards functions as a receiver daughterboard able to operate within the DC to 30 MHz frequency band. The LFRX does not provide an RF front end, but it is able to receive a raw signal. The LFRX also provides control pins that are connected to I/O ports on the FPGA, and are controlled using special commands provided by GNU Radio.

The LFRX daughterboard served as our receiver front end allowing us to capture the signal coming from the preamplifier. The signal was then passed on to the USRP where it was converted to a digital form with the use of ADCs. The FPGA processed the signal and transferred it to the host computer via Ethernet. Once the signal had reached the host computer, the signal
was further processed and demodulated using the processing blocks provided by GNU Radio. We were then able to obtain the information and decode.

4.2.4 Neighbor Discovery and MAC Protocol Development
In this section, we focus on the construction of the neighbor discovery and MAC protocols. We give details on how the protocols were implemented, and provide details on the different processing blocks that were used to create our transmitter and receiver paths.

4.2.4.1 GNU Radio
As previously mentioned, GNU Radio is an open source software developed to work with software radios or in simulation like environments. GNU Radio is based on Python and C++, and made to run on a Linux platform. The basic idea behind GNU Radio is in the creation of signal blocks and flowgraphs. Signal blocks allow us to perform signal processing on incoming or outgoing signals. A number of different signal blocks are available within the GNU Radio libraries that provide different functionalities. Different settings are given within these blocks that allow a user to select among different data types, gains, sample rates, and bit rates. C++ is used to implement the different processing blocks found within GNU Radio. Some of the blocks found in GNU Radio library can be seen in Figure 4.8. Flowgraphs consists of a number of interconnected signal blocks that create transmitter and receiver paths. The input and output ports of the various blocks are connected by the user. Python is used implemented, and manage the operation of the flowgraphs. The Simplified Wrapper and Interface Generator (SWIG) is used to ease the transfer of information between Python and C++. Although GNU Radio is well developed, very limited information is available for new users. Most of our work consisted of manually tracing variables from one file to another in order to gain better understanding of their functionality. Online forums do exists were one can go and share information with other developers. Overall, GNU Radio provided a software framework that we used to implement our communication system.
<table>
<thead>
<tr>
<th>Sources</th>
<th>Sinks</th>
<th>Operators</th>
<th>Type Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Source</td>
<td>Vecotr Sink</td>
<td>Add</td>
<td>Complex to Mag</td>
</tr>
<tr>
<td>Constant Source</td>
<td>Null Sink</td>
<td>Subtract</td>
<td>Complex to Arg</td>
</tr>
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<td>Noise Source</td>
<td>File Sink</td>
<td>Multiply</td>
<td>Complex to Real</td>
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<tr>
<td>Null Source</td>
<td>Message Sink</td>
<td>Divide</td>
<td>Complex to Float</td>
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<tr>
<td>Vector Source</td>
<td>Virtual Sink</td>
<td>Multiply Const</td>
<td>Float to Complex</td>
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<td>Audio Sink</td>
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<td>Wav File Sink</td>
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<tr>
<td>Wav File Source</td>
<td></td>
<td>Xor</td>
<td>Char to Short</td>
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<td>Synchronizers</td>
<td>UHD</td>
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<td>Digital Filters</td>
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<td>Packet Encoder</td>
<td>USRP Source</td>
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<td>QAM Mod</td>
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<td>Simple Framer</td>
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<td>FFT Filter</td>
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<td>IIR Filter</td>
<td>GMSK Mod</td>
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<tr>
<td>PLL Freq Det</td>
<td></td>
<td>Dec FIR Filter</td>
<td>GMSK Demod</td>
</tr>
</tbody>
</table>

Figure 4.8: Signal blocks provided by GNU Radio
4.2.4.2 Software Transmitter and Receiver Design

Although the operation of the neighbor discovery and MAC protocol is different, the manner in which their information is processed, modulated/demodulated, and transmitted/received is the same. The protocols initially handle the development of the information that is to be transmitted. Packets of information are created within our Python protocols that are structured according to the protocol currently in operation. The packets are then transferred to the flowgraphs were the information gets processed. We developed two different sets of transmitter and receiver flowgraphs that were used to implement our UV communication system.

In the first flowgraph design (Figure 4.9), a packet gets transferred to the Packet Encoder. The Packet Encoder adds a header to our packet consisting of an access code and preamble. Both the access code and preamble serve to synchronize the transmission timing of the two systems. A

Figure 4.9: Structure of first transmitter and receiver flowgraph design
cyclical redundancy check (CRC) is also added at the end of the packet that provides error
detection. The Encoder allows you to select the samples/symbol and bits/symbol for your
transmission. The signal is then passed on to our modulation block. Our modulation block maps
our “1” bits to a constellation point of 1+0j, and our “0” bit to a constellation point of 0+0j. Thus,
achieving On Off Keying using a pulse to represent a 1, and the absence of a pulse to represent 0.
Our OOK modulation block allows us to select the desired samples/symbol and excess bandwidth.
The final component of our transmitter consists of a USRP Sink. At this point, the information is
transferred to the USRP via Ethernet port and transmitted.

Our receiver consists of the components that can be seen in the receiver portion of Figure
4.9. The signal is initially captured with the use of a USRP Source signal block. The USRP
Source block transfers the received information from the USRP to host computer. The signal then
travels into the OOK demodulation block. At this point, the information is demodulated, and
returned in a packet format. The packet now enters the Packet Decoder block which removes the
access code, preamble, and crc information added by the Packet Encoder. The original packet is
returned to our Python program where our protocols react to the received information. The
different parameters that are available for each block can be seen in Figure 4.9.

4.2.4.3 Software Transmitter and Receiver Design 2

Our second transmitter and receiver flowgraph design can be seen in Figure 4.10. The
packet of information that is created by the Python protocols is written to a file. A File Sink block
is then used to retrieve the information from the file. The packet then enters the Packed to
Unpacked block were it gets broken down to individual bits. A Chunks to Symbols block allows
us to map a “1” bit to a pulse, and the absence of a pulse to a “0” bit. A USRP Sink block is then
used to transmit the information.
In the receiver portion of the flowgraph, the information is initially captured by a USRP Source block. The data type of the information is changed from complex to real using a Complex to Real block. A Threshold block is then used to map a high signal to 1 and a low signal to 0. Our data therefore only consist of 1s and 0s. The information is then transferred to a Vector Sink where it gets stored. A program developed by Linchao Liao at the University of California, Riverside is then used to retrieve the information from the Vector Sink block. The information stored within the Vector Sink is very large. The program developed by Linchao reduces the information and groups it into 8 bit groups. The groups represent characters that were transmitted. The program then converts the 8 bit groups into the characters that were originally transmitted. Once the original data is obtained, the Python protocols are allowed to react to the received information.

![Flowgraph Design](image)

Figure 4.10: Structure of second transmitter and receiver flowgraph design
4.3 Summary

In this chapter, we presented the steps that were taken to achieve the implementation of our ultraviolet communication system. The transceiver that handles the transmission and reception of our signals was built. The different hardware devices that compose our transmitter and receiver chains were introduced. We explained how each component was integrated into our communication system, and covered the overall functionality of our system. The design of the software transmitter and receiver paths was also introduced. Details were given on the signal blocks and flowgraphs that processed our incoming and outgoing signals.
Chapter 5 UV System Experimental Results

5.1 UV Communication System Setup

The experiments were performed on the testbed that can be seen in Figure 5.1. Our transmitter consists of a USRP, an LED driving circuit, and a number of LED transmitters. The information is initially created and structured according to the Python program currently in operation. The program can be either running the neighbor discovery or MAC script. A signal is then created within the USRP that carries the information that is to be transmitted. The signal then leaves the USRP and is fed into the LED driving circuit. The signal from the driving circuit is passed to a number of LED transmitters that operate within the 250 nm wavelength. The LED transmitters are used to transmit UV signals carrying the information. The LEDs are controlled by the control pins found on the transmitter daughterboard. Our receiver consists of a PMT, a low noise current preamplifier, and a USRP. The PMT initially captures the optical signal and produces a current signal that is fed to the preamplifier. The preamplifier produces a voltage signal that is proportional to input current. The voltage signal is fed into the USRP where the signal is processed and demodulated. The protocol in operation then decodes the information and reacts accordingly. Further information on the different components of the testbed can be obtained in Chapter 4.
5.2 Transceiver Design Verification

Initially, a number of experiments were performed that allowed us to verify the operation of the transceiver. We wanted to make sure that the transceiver was able to properly transmit and receive information using ultraviolet light. During these experiments, a packet of information was continuously transmitted. Both pairs of transmitter and receiver flowgraphs were used to transmit and receive information. An oscilloscope was connected to the output of the preamplifier allowing us to view the shape of the waveform that was being received. After visually verifying the form of the signal, we connected the output of the preamplifier to the USRP. The transceiver was then allowed to process and decode the information. The transceiver was not able to properly decode the information that was being transmitted using the first flowgraph design. Our OOK demod block seemed to be the source of the problem. The block was simply not able to demodulate the information that was being received. We abandoned this approach because we were not able to get the block to function. The second flowgraph design was then tested. After a
couple of minor adjustments, the packets of information were able to properly obtained and decoded. The rest of the experiments were therefore performed using the second flowgraph design.

5.3 MAC and Neighbor Discovery Results

5.3.1 Experimental Setup
Multiple experiments were performed to help us better understand the overall performance of our communication system. The data obtained from the experiments was used to compute the bit error rate and path loss experienced by our communication system. The experiments were performed with the use of two transceivers. The two transceivers were placed on movable tables as can be seen in Figure 5.1. The transceivers were initially separated by a distance of three meters. Tests were performed, and the distance was then increased by two meters. We continued in this manner until seven meters was reached. At this distance, the received signal was very weak, and only some of the information was able to be retrieved. At every distance, we varied both the transmitter and receiver pointing angles. The transmitter pointing angle was changed between 30° and 50°. The receiver pointing angle was varied from 10° to 90°. During every test, the receiver pointing angle was increased by 20° until 90° was reached. Information was transmitted from one transceiver to another in both directional and omni-directional mode. The two modes were considered because they are both used in our protocols to transmit information. Therefore, information was captured when only one pair of LEDs was turned on (directional mode), and when all 5 pairs of LEDs were on (omni-directional mode). The BER test consisted of the transmission of a single package. The package contained a header, a payload, and a tail. At the receiver, a PMT was used to capture the signal. The captured signal was then decoded and compared with the transmitted information. The package was transmitted multiple times at every angle. We then computed the average BER that was obtained for each
angle that was tested. For the path loss test, we obtained the number of photons that were received during the transmission of a single pulse. A photon counting program developed by Linchao Liao at WIT Lab was used to count the number of received photons. We verified the number by manually counting the number of photons that were received during each pulse with the help of an oscilloscope. The test was performed with the output of the PMT connected directly to the USRP and oscilloscope. The low noise current preamplifier was not used during the path loss experiment. The basic operation of both protocols was then tested by simply allowing the nodes to run the MAC and neighbor discovery scripts. Pictures and video were taken which capture the operation of the nodes.

5.3.2 Bit Error Rate Results

The MAC and neighbor discovery protocols were implemented using the GNU Radio software framework. Although each protocol uses a different set of data packages, the transmitter and receiver paths operate in the same manner. Therefore, the results obtained in directional and omni-directional modes can be used to characterize the performance of both protocols.

For our BER results, we transmitted a total of 20 packages within a 20 second interval. The packages were transmitted every second for 20 seconds. After the packages were received, the received information was compared to the transmitted information. A counter was used to record the number of incorrect bits that were received. The counter containing the number of incorrect bits was then divided by the total number of transmitted bits. The result gave us the BER that was experienced for that package. The average BER was then calculated from BERs that were obtained from the 20 packages that were transmitted. A package consisted of a header, a payload, and a tail. The header contained a total of 5 “b”s. The payload consisted of a 1,000 “a”s, while the tail was a single “c”. The total number of bits that was transmitted was 8048. Only the payload was considered when the BER was being calculated. Once the BER was obtained, we
attempted to decode the information that was received, and the protocol was allowed react accordingly.

The results obtained at a distance of 3 meters can be seen in Figure 5.2. From the results, we are able to see that we obtained a lower BER for lower receiver pointing angles. This is expected considering that at lower pointing angles line of sight links between a transmitter and a receiver can be assumed. As the pointing angle of the receiver increases, the BER grows exponentially. At larger receiver pointing angles, the communication between a transmitter and receiver can be considered as a non-line of sight link. This result is also expected considering the common volume theory. The overlap volume between the transmitter’s beam and receiver’s field of view decreases as the pointing angle of the receiver increases. Therefore, we can assume that less photons are received by the PMT.

From the figure, we are also able to see that when all 5 directions are used (omni mode) the BER is considerably lower than in the case when only one direction (directional mode) is used for communication. In this case, we believe that the multiple scattering of the different directions helps reinforce the signal that is being received by the PMT. The common volume between the transmitter and receiver is larger. Therefore, more photons are received and the signal is much stronger. In this configuration, the information is able to be properly received and decoded.

The figure also allows us to see that the transceiver performs better when the transmitter angle is 50°. The BER that is obtained is much lower when compared to the graphs where the transmitter pointing angle is 30°. At this distance, we can again assume the volume between the transmitter’s beam angle and receiver’s FOV is much large when transmitter has a pointing angle of 50°.
Figure 5.3 presents the BER results obtained for a transceiver separation distance of 5 meters. As we can see, the BER also grows exponentially as the receiver pointing angle increases. Therefore, the conclusion we had previously made about the exponentially increasing BER can also be used to characterize the results obtained for 5 meters. From the figure, we are also able to see that the results are similar when 1 direction or all 5 directions are used for communication. At this distance, the signal does not seem to be reinforced by the usage of all 5 directions. We are also able to see that the overall BER obtained at this distance is also considerably larger than the previous distance. This may be due to the fact that path loss increases by the distance squared. As the distance increases, the power of the optical signal drops considerably. Less photons are received, and errors begin to appear within the received information. Thus, it becomes much more difficult to decode the information that is received.
The system also seems to perform better when the transmitter angle is 30°. We can assume that this occurs because the overlap volume between the transmitter and receiver is much larger when the transmitter pointing angle is 30°. When the transmitter pointing angle is 50°, the overlap volume is likely to be smaller. Therefore, a signal with less optical power is received.

Figure 5.3: BER results at 5 meters

Lastly, Figure 5.4 shows the results obtained for a distance of 7 meters. The results are again very similar to those obtained for a distance of 3 meters and 5 meters. The BER again grows exponentially as the receiver pointing angle is increased. The number of directions used for communication does not seem to have an effect on the BER. The results are similar for the two modes that are used. The system again performs better when the transmission pointing angle is 30°. At this distance, the received signal with a receiver pointing angle of 90° was very weak. Most of the information was not able to be obtained or decoded. Therefore, the BER at this angle was very high, and at times no information was able to be received. This may be due to the fact
that the LEDs we were using simply did not provide enough power. In future experiments, the use of LEDs with higher output powers or an LED array may be considered in order to increase the distance the signal can reach.

![Figure 5.4: BER results at 7 meters](image)

5.3.3 Path Loss Results

The path loss experiment consisted of counting the number of photons that were received during the transmission of a single pulse. A pulse was continuously transmitted by the transceiver for an interval of 1 minute. The pulse was transmitted when the transceiver was in both directional and omni-directional modes. Therefore, the results obtained in either mode can be used to characterize the performance of both protocols.

The test was performed with the output of the PMT connected directly to the USRP and oscilloscope. The low noise current preamplifier was not used during this experiment. A photon
counting program developed by Linchao Liao at WIT Lab was used to count the number of received photons. We verified the number by manually counting the number of photons that were received during each pulse with the help of an oscilloscope. As mentioned earlier, PMTs produce a current in response to a received UV signal. A spike is created that corresponds to the arrival of a photon. When the channel quality is good, a number of spikes will be produced by the PMT, meaning that a number of photons were received. By counting the spikes, we were able to count the number of photons that were received for a particular pulse. We then averaged the number of photons that we obtained during the transmission of the pulses. The path loss was then calculated according to equation 5.1 [37]:

$$R = \frac{\eta_f \eta_r P \lambda}{hcLN_d}$$  \hspace{1cm} (5.1)

In equation 5.1, the $R$ represents the data rate, $\eta_f$ is the filter transmission efficiency, $\eta_r$ is the receiver detection efficiency, $P$ is the transmitted power, $\lambda$ is the UV wavelength, $h$ is Planck’s constant, $c$ is the speed of light, $L$ is the link path loss, and $N_d$ is the number of photons detected per pulse. Our experiment was performed with a $\lambda = 266$nm, $\eta_f = 0.3$, $\eta_r = 0.2$, and $R = 50,000$ Hz. For a single LED, we measured a transmitted power of $1.448$mW. Therefore, we decided to use a transmitted power of $2.896$mW for the directional mode, and $10.374$ for the omni directional mode.
Figure 5.5: Path loss results while transmitting in one direction

Figure 5.5 presents the path loss results we obtained with a transmitter pointing angle of 30° and 50° with the transceiver in directional mode. We can observe that the path loss experienced at lower receiver pointing angles seems to be around 87 dB in most cases. As the receiver pointing angle increase, the path loss that is experienced by the system also increases. The system seems to experience the same amount of path loss in most cases. The exception seems to be when the transmitter pointing angle is 50° with a distance of 3 meters. At this distance, the
path loss decreases slightly as the receiver pointing angle increases. This may be due to the position of the transceivers during the experiment. The transmitter and receiver might have had a similar height level. Therefore, the common volume between the transmitter’s beam and the receiver’s FOV must have been larger at higher pointing angles.

![Graph showing path loss results](image)

Figure 5.6: Path loss results while transmitting in all 5 directions

In Figure 5.6, we present the path loss results obtained with the transceivers in omni-directional mode. The results seem similar to those obtained when the transceivers were in the
directional mode. The system seems to initially experience a path loss of 92 dB. As the receiver pointing angle increase, the path loss that is experienced by the system also increases. The system seems to experience the same amount of path loss in most cases. From the results, we can conclude that the use of 5 directions does not seem to reduce path loss that the system experiences in a specific direction. We should keep in mind that the transceiver is pointing in different direction. Therefore, using every direction may not help reinforce the signal that is received in a specific direction. A lower path loss may be achieved if LEDs with higher output powers are used. The use of LED arrays should also be considered if a stronger signal needs to be received.

5.3.4 Neighbor Discovery Test Results

The results obtained in the previous two experiments, allowed us to discover the best configuration to use during the testing of our protocols. By best configuration we mean the distances and pointing angles that achieved the lowest path loss and BER. The configuration consisted of having a transmitter pointing angle of 50° and a receiver pointing angle of 40°. Other configurations could be used, but these pointing angles allowed us to establishing a NLOS link for communication. The nodes were also set apart by a distance of half a meter. The nodes were then allowed to run the neighbor discovery and MAC script. The images that are presented were captured during the operation of the nodes. A number of images have letters and numbers in their top portion. These letters and numbers simply represent the data that was received.

Figure 5.7 shows the initial states of the two nodes. As we can see, both nodes begin with empty Connection, Receiving Node, and Termination Tables. The top image shows that one of the nodes (node 1) begins by being in a Standby state where it simply listens to the medium and decodes any information it receives. This node can be considered as the neighbor node. From the bottom image, we are able to see that the other node (node 2) was selected as the leader and has
initiated the neighbor discovery process. The leader sent a total of 5 request packets, one in every direction. The leader then entered the Wait for Feedback state where it waits to receive a response from its neighbor.

![Initial states of nodes during neighbor discovery](image1)

![Initial states of nodes during neighbor discovery](image2)

Figure 5.7: Initial states of nodes during neighbor discovery

From the top image of Figure 5.8, we can see that the neighbor node that was in the Standby state received the request packet. The request packet contained the address of the leader (address 2) and the direction that it used to sent it (direction 5). The node then replied with a feedback packet containing its address (address 1) and the direction that leader initially used to send the request packet (direction 5). The neighbor node then returned to the standby state.
The bottom image allows us to see that the leader was able to successfully receive the feedback packet. The leader proceeds to construct its Connection, Receiving Nodes, and Termination Tables. The Termination Table was updated, and shows that the node served as the leader once. The leader then selects its successor (node 1), and transmits a notify packet allowing the node to become aware that it was selected as the leader. The node then proceeds to enter the standby state.
Using Figure 5.9, we can now see that the neighbor has received the notify packet and the Termination Table. The node then proceeds to continue the neighbor discovery process. The process continues until both nodes have marked themselves as being finished with the neighbor discovery process. At this point, the process terminates, and the MAC begins its operation.

5.3.5 MAC Test Results

After the neighbor discovery results were obtained, tests were performed on the MAC to better understand its performance. During the tests, the nodes were assumed to have their neighborhood information. The nodes contained the addresses and the directions they could use to communicate with their neighbors. The nodes were then allowed to run the MAC script.

Figure 5.10 gives us the initial states of the two nodes during the MAC test. From the images, we are able to see that both nodes have Connection and Receiving Nodes Tables containing their neighborhood information. The top image allows us to see that node 2 is in the idle state. The node is able to simply listen to the medium and decode any information it receives. The bottom image shows that the node 1 has information to send. Node 1 has proceeded to send a CTS message, making its neighbor aware that it has pending data to send. After node 1 has finished sending the CTS message, node 1 enters the Wait for CTS state where it waits to receive a response.
Using Figure 5.11, we are able to see that node 2, initially in the Idle state, was able to receive the RTS message from node 1. The node was also able to conclude that the RTS message was addressed to it. Node 2 proceeds to respond by transmitting a CTS message. Once it has finished transmitting, it enters the Wait for Data state where it waits to receive the information. Figure 5.11 also allows us to see that a CTS message was successfully received by node 1. We are able to see that the CTS message was transmitted by node 2 and was addressed to node 1. Node 1 responds by transmitting the pending data. Once node 1 has finished transmitting the data, it enters the Idle state.
Lastly, Figure 5.12 shows node 2 receiving the data from node 1. The information was sent using direction 1. Node 2 is now able to return to the Idle state.
5.3.6 Results Analysis

The results that were obtained during the experiments allow us to verify the performance of our UV communication network. We have shown that our system transceivers are able to transmit and receive information using the UV spectrum. Once the information is received, the transceiver is able to process it and retrieve what was transmitted. The BER results show that enough of data can be correctly received allowing us to react accordingly within our MAC and neighbor discovery protocols. The path loss results allow us to verify the results that were obtained during our BER experiment. We are able to see that at higher receiver pointing angles the path loss that is experienced is high. Therefore, the signal is weak, and the data may be corrupt. Therefore, it will be difficult to obtain the original information.

We were also able to verify the basic operation of both our protocols. From the results, we are able to see that a node is able to react accordingly to the information it receives. The nodes were able to find each other during the neighbor discovery process. They were able to obtain the address of its neighbor and the direction it could use to communicate with it. Once a node contained this information, the MAC protocol was used to exchange information.

5.4 Future Work

Although our system served as a testbed, additional work needs to be performed in order to enhance the performance of our communication network. Modifications at both the system and physical level should be considered in order to continue the progress that has been made.

At a system level, better detection schemes should be developed in order to improve the detection of UV signals. A better detecting scheme would allow us to lower the bit error rate that the system experiences. More of the information would be received and decoded due to the better quality of the signal. Different modulation schemes should also be considered and tested in order
to understand their impact on the performance of the communication system. The system may benefit from the ability to switch from one modulation scheme to another. The cost of the communication system must also be addressed. Certain components that were used for the system are very expensive. If the cost cannot be lowered, the system will not be practical enough to be implemented in real life.

The design of both of our protocols can also be modified in order to increase their efficiency and versatility. Modifications can be made which would decrease the time needed to discovery a node’s neighbors. By decreasing the discovery time, the network is able to be more rapidly configured. Moreover, the design of Practical UVOC-MAC can also be modified to allow full duplex communication. Full duplex communication would increase the throughput that can be achieved by the communication channel. Both protocols can be modified to account for node mobility. Node mobility is necessary if the communication system is going to be used by soldiers on a battlefield. Moreover, other MAC and neighbor discovery protocols have to be developed that are able to take better advantage of the UV channel characteristics. The design of high layer network protocols would allow us to better control the manner in which the UV channel is being used for communication.

At the physical level, further research is needed to better understand the UV channel characteristics. Models that account for multiple scattering should be developed in order to better understand how UV signals propagate. The effects of non coplanar interference between transmitters and receivers should also be looked into. Non coplanar interference may cause severe issues in an ongoing communication if it is not accounted for.
5.5 Conclusion

This thesis explores different aspects of an optical communication network. Neighbor discovery and MAC protocols are studied and designed to operate within the UV spectrum. The unique UV channel characteristics are taken advantage of and used for non-line of sight communication. The thesis then focuses on the implementation and construction of an optical communication system.

A leadership based neighbor discovery protocol is designed that is able to handle the initial configuration of the communication system. The protocol creates an interference free environment that helps reduce the time required for neighbor discovery. The protocol is based on the sequential discovery of a node’s neighbors. At the termination of the protocol, a node is able to know the addresses of the neighbors that surround it, and the directions that it can use to communicate with them.

A medium access control protocol is proposed to moderate access to the medium making the communication among devices orderly and efficient. Practical UVOC-MAC is a random access based protocol designed for an outdoor ad hoc network. The design of Practical UVOC-MAC is tied to the UV PHY layer properties which allow the use of non-line of sight links for communication. Spatial reuse is achieved by the protocol by allowing it to adaptively choose the direction of the communication.

A test bed is constructed that allowed the implementation of the optical system. A software defined radio is used to construct the transceivers that are able to exchange information using the UV channel. Descriptions and details on the different hardware components that are used for the transmitter and receiver paths are presented. An explanation on how each component is integrated into the communication system is also given. A software framework is used to
implement the neighbor discovery and MAC protocols. Preliminary results on the performance of the communication system test bed are reviewed. The bit error rate and path loss are used to evaluate the performance of the communication system at different distances and pointing angles.
Bibliography


